Appendix G

Concrete Properties

Concrete is a mixture of aggregates (sand and gravel), entrained air, cement, and water. A chemical reaction between the cement and the water causes concrete to harden. This reaction is known as hydration. Concrete is, at first, a plastic mass that can be cast or molded into nearly any size or shape. When hydrated, concrete becomes stonelike in strength, durability, and hardness. The strength of concrete depends on the water-to-cement ratio used in the concrete mixture. Generally, the less water in the mix, the stronger, more durable, and watertight the concrete. Too much water dilutes the cement paste and results in weak concrete.

GENERAL PROPERTIES

G-1. A sack of cement requires about 2 1/2 gallons of water for hydration. However, more water will improve the workability of plastic concrete. Normally, concrete mixtures will use 4 to 7 gallons of water per sack of cement.

G-2. *Table G-1* shows the approximate compressive strengths of concrete for various water-to-cement ratios. To classify bridges with unknown concrete strength, assume a compressive strength of 3,000 psi.

Table G-1. Maximum Permissible Water-to-Cement Ratios for Concrete

Specified Compressive Strength (f′c) (psi)[1]	Maximum Absolute Permissible Water-to-Cement Ratio (by Weight)	
	Nonair-Entrained Concrete	Air-Entrained Concrete
2,500	0.67	0.54
3,000	0.58	0.46
3,500	0.51	0.40
4,000	0.44	0.35
4,500	0.38	See note 2
5,000	See note 2	See note 2

NOTES:

1. This value refers to the 28-day strength. With most materials, the water-to-cement ratios shown will provide average strengths greater than required.

2. For strengths above 4,500 psi (nonair-entrained concrete) and 4,000 psi (air-entrained concrete), proportions should be established using the trial-batch method.

1,000 psi ≈ 7 megapascal

G-3. Concrete is among the best and most important building materials. Concrete is fireproof, watertight, comparatively economical, and easy to prepare. It offers surface continuity and solidity and bonds with other materials. Concrete is used in bridging to make abutments, intermediate supports, columns, beams, slabs, decks, curbs, and handrails. Concrete offers good compressive strength and has a long service life. Certain limitations of concrete cause cracking and other structural weaknesses that detract from its appearance, serviceability, and useful life. Some limitations of concrete are discussed below.

LOW TENSILE STRENGTH

G-4. Concrete members subject to tensile stresses must be reinforced with steel bars or mesh. This will prevent cracking and failure.

THERMAL MOVEMENTS

G-5. During setting and hardening (curing), the heat of hydration raises the concrete temperature and then gradually cools. The temperature changes can cause severe thermal strain and early cracking. Also, hardened concrete expands and contracts with changes in temperature at roughly the same rate as steel. Therefore, provide expansion and contraction joints in concrete constructions.

DRYING, SHRINKAGE, AND MOISTURE MOVEMENT

G-6. Concrete shrinks as it dries out and, even when hardened, expands and contracts with wetting and drying. These movements require control joints to avoid unsightly cracks. To prevent drying shrinkage and cracks, keep the surface of newly placed concrete moist during the curing process.

CREEP

G-7. Concrete gradually deforms (creeps) under load. The concrete does not recover completely when the load is removed. Over time, creep may reduce the structural soundness of the bridge.

PERMEABILITY

G-8. Concrete is not entirely impervious to moisture. It contains soluble compounds that may be leached out by water.

HYDRATION

G-9. To hydrate concrete properly, keep the temperature of the concrete above $50^{o}F$ during the early curing process of the concrete. Trying to maintain the minimum required temperature causes some additional problems when placing concrete in cold weather.

CEMENT TYPES

G-10. Different types of cement have been developed to offset some of the limitations of using concrete in structures. The ASTM specifications cover five types of portland cements.

TYPE I

G-11. Type I is a general-purpose cement for concrete work that does not require any of the special properties of the other types. In general, it is used when concrete structures are not subject to sulfate attack or when the heat of hydration will not cause too great a temperature rise. Type-I cement is used in pavement and sidewalk construction, reinforced concrete buildings and bridges, railways, culverts, and soil-cement mixtures. Do not use Type-I cement where it will come into contact with sea water. Type-I cement reaches its design strength in 28 days.

TYPE II

G-12. Modified to resist moderate sulfate attack, Type-II cement generally generates less heat of hydration and cures at a slower rate than Type-I cement. In general, it is used in drainage structures where the sulfate concentrations in either the soil or the groundwater are higher than normal, but not severe, and in large structures when the moderate heat of hydration produces only a slight temperature rise in the concrete. However, temperature rise can be a problem when Type-II cement is placed during warm weather. Type-II cement reaches its design strength in 45 days.

TYPE III

G-13. Type-III cement achieves a high design strength very quickly in the curing process (usually 7 days or less). It has a higher heat of hydration and is more finely ground than Type-I cement. Type-III cement permits fast form removal and, in cold weather construction, reduces the period of protection against low temperatures. Although richer mixtures of Type I can obtain high design strength at an early stage, Type-III cement produces this early strength more satisfactorily and economically. Use Type-III cement cautiously in concrete structures having a minimum spacing of 2 1/2 feet or more because the high heat of hydration can cause shrinkage cracking.

TYPE IV

G-14. Type-IV cement has a low heat of hydration and is intended for applications requiring a minimal rate and amount of heat of hydration. Its strength also develops at a slower rate than other types of cement. Use Type-IV cement primarily in very large concrete structures, such as gravity dams, where the temperature rise from the heat of hydration could damage the structure. Type-IV cement reaches its design strength in 90 days.

TYPE V

G-15. Type V is a sulfate-resistant cement and is used mainly for applications where the concrete is subject to severe sulfate action, such as when the soil or groundwater in contact with the concrete has high concentrations of sulfate. Type-V cement reaches its design strength in 60 days.

AIR-ENTRAINING CEMEMTS

G-16. Types IA, IIA, and IIIA correspond in composition to Types I, II, and III, respectively, with the addition of small quantities of air-entraining materials ground into the clinker during manufacture. Air-entraining cements produce concrete having improved resistance to freeze-thaw action and to scaling caused by snow- and ice-removal chemicals. Such concrete contains extremely small, well-distributed (as many as 3 billion per cubic yard), and completely separate air bubbles.

MASONRY CEMENTS

G-17. Masonry cements (sometimes called *mortar cements*) are typically mixtures of portland cement, hydrated lime, and other materials. This mixture improves the workability, plasticity, and water retention of the cement.

MASS-CONCRETE STRUCTURES

G-18. Some structural members are made of solid concrete (little or no steel reinforcement). Generally, these concrete structures are in compression only and require massive weight to be effective. Examples of members that may be solid concrete are abutments, suspension-bridge cable anchors, masonry arches, and gravity dams. Concrete structures (even those in complete compression) will normally have some reinforcing steel to provide internal strength.

STEEL-REINFORCED CONCRETE

G-19. Steel-reinforced concrete is used in almost all concrete structures. Since concrete has poor tensile strength (it breaks easily when pulled apart), steel has to be added to structural members to accommodate the tensile forces. On the other hand, while steel is better at carrying tensile force, it has the tendency to buckle when compressed. Therefore, when the two materials are combined, one makes up for the deficiency of the other. When steel reinforcement in concrete helps carry loads, the combination is called reinforced concrete. A reinforced concrete structure takes many forms—beams, columns, girders, walls, footings, slabs, and so forth. See *FM 5-428* for more specific information on steel reinforcement.

BEAM REINFORCEMENT, SIMPLY SUPPORTED BEAMS

G-20. When a simply supported beam is loaded, the top of the beam receives compressive stresses and the bottom of the beam receives tensile stresses. This condition can easily be visualized by bending a pencil up and observing the shortening of the top fibers (compression) and the lengthening of the bottom fibers (tension). In the compression area of the beam (top), no steel reinforcement is necessary because concrete is strong under compression. However, in the tension area of the beam (bottom), steel reinforcement is necessary to carry the tensile forces.

BEAM REINFORCEMENT, CONTINUOUSLY SUPPORTED BEAMS

G-21. The tension areas in continuous beams (beams supported by three or more supports) are found on the top and the bottom of the beam, depending on the location along the beam being analyzed and the position of the load. At the center of a continuous span, the top of the beam is in compression and the bottom is in tension (similar to a simply supported beam). The tension-reinforcing steel is located in the bottom portion of the beam. Over the intermediate support(s) of a continuous beam, the top of the beam receives tensile stresses, so the reinforcing steel is located in the top portion of the beam over the intermediate support(s).

BEAM REINFORCEMENT, BAR REPLACEMENT

G-22. *Figure G-1* shows common shapes of reinforcing steel for beams. The purpose of both straight and bent-up bars is to resist the bending tension in the bottom of a beam. A beam requires fewer bars near the ends of a span because the bending moment is smaller near the span ends than at the span center. However, the shear forces are larger at the span ends, and this condition causes diagonal tension in the beam. This area is where the inclined portion of the bent-up bar is placed to resist the diagonal tension due to shear. The bent-up portion of reinforcing bars for continuous beams continues across the intermediate supports to resist top tension in the support area. When the bent-up bars cannot resist all of the diagonal tension, U-shaped bars (called stirrups) are added. Because of the tensile stress on the stirrups, they pass under the bottom bar and are inclined or perpendicular to it to prevent slippage.

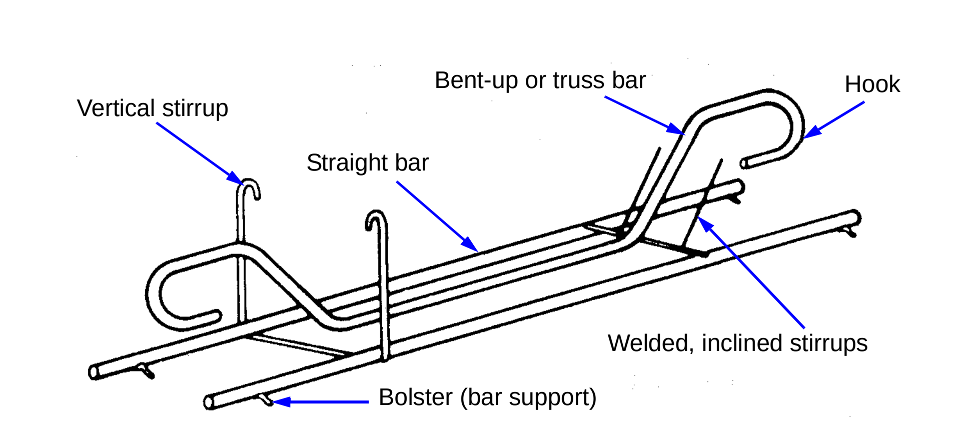


Figure G-1. Typical Shapes of Reinforcing Steel for Beams

SLAB-DECK REINFORCEMENT

G-23. Slab decks are usually continuous over each of the stringers on a bridge. Tension exists in the top and bottom portions of the slab as a load is applied. Steel reinforcement is necessary in the top and bottom portions of slab decks, perpendicular to the stringers *(Figure G-2, page G-6)*. Besides the main reinforcement of concrete slabs, reinforcement comes from the distribution steel that is placed perpendicular to the main reinforcing steel. Distribution steel—

- Carries tensile forces caused by changes and stresses induced by temperature.

- Is located in the bottom portion of the slab.
- Is also used in the top portion to tie the main reinforcement in place properly and to strengthen the slab.

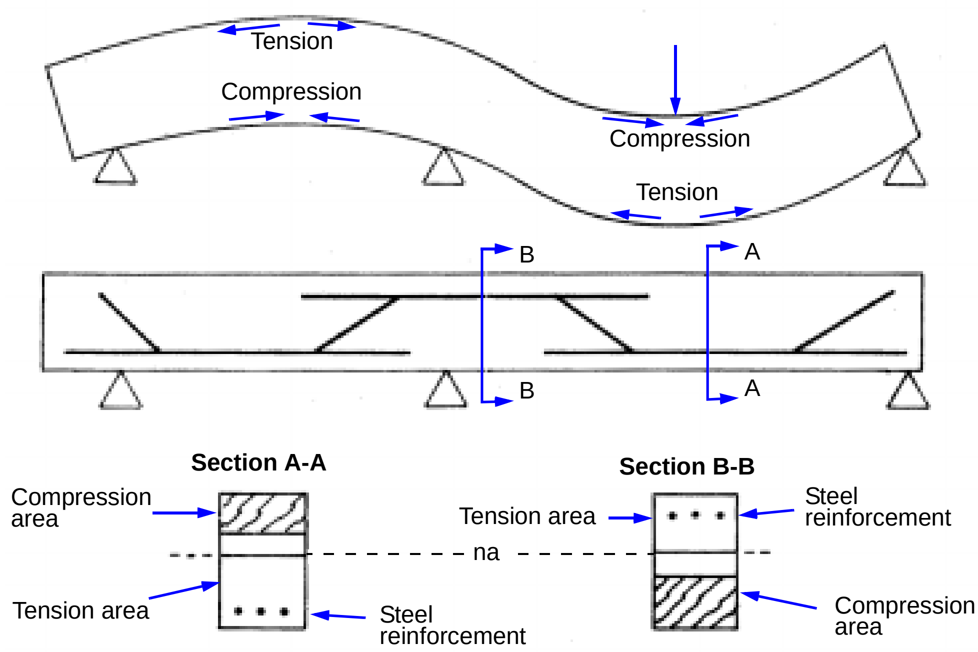


Figure G-2. Reinforcement Placement in Continuous Beams or Slabs

COLUMN REINFORCEMENT

G-24. A *column* is a slender, vertical member that carries a superimposed load. When the structure's height is less than three times its least lateral dimension, this structure is known as a *pier* or *pedestal*. Concrete columns must always have steel reinforcement because they are subject to bending. *Figure G-3* shows two types of column reinforcement. Vertical reinforcement is the main type. Lateral reinforcement consists of individual ties or a continuous spiral that surrounds the column.

FOOTING REINFORCEMENT

G-25. Steel reinforcement in footings and slabs that rest on the ground is located in the bottom portion of the footing since the bottom portion receives the tensile forces. The steel is placed so it runs in two directions, forming a series of squares or a grid *(Figure G-4)*.

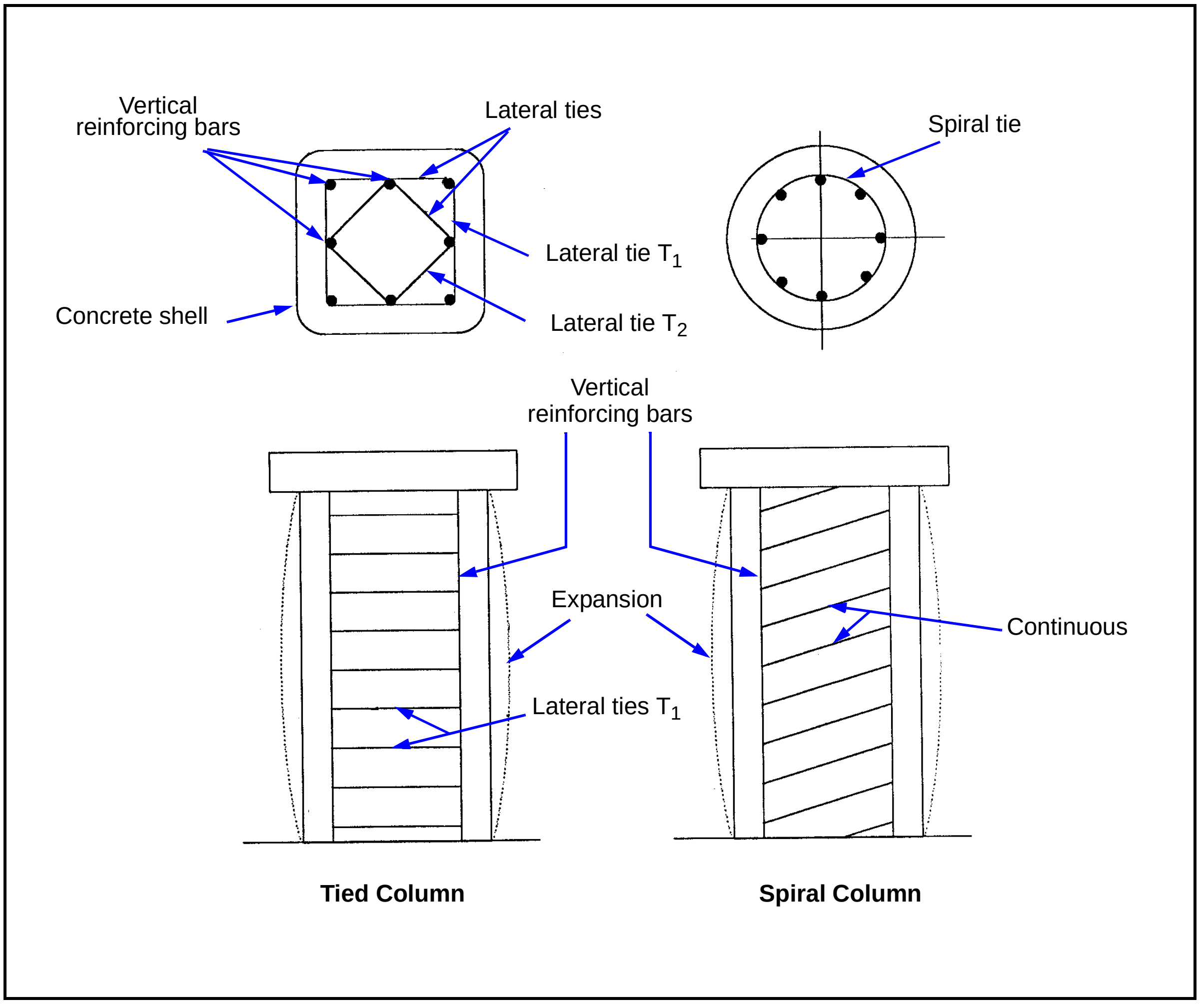


Figure G-3. Reinforced Concrete Columns

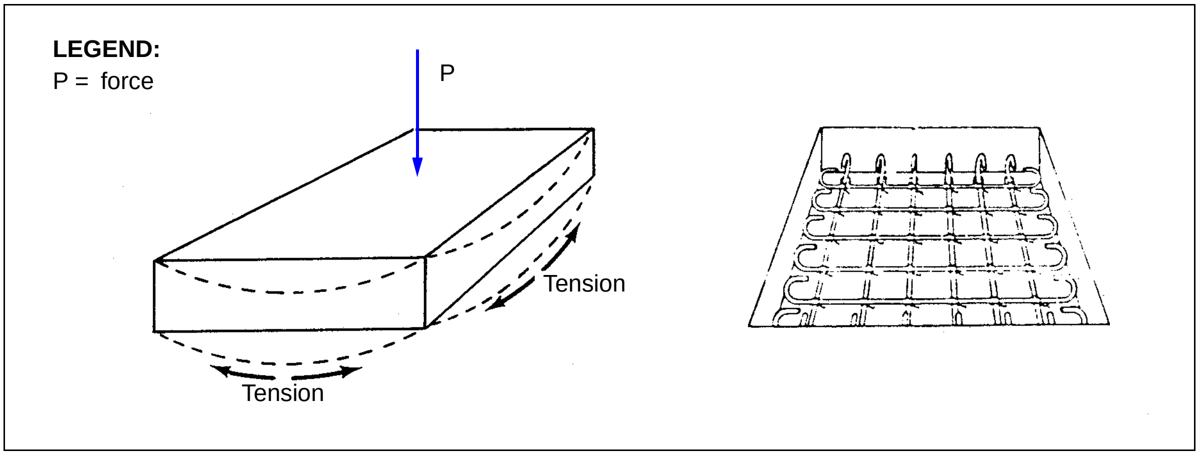


Figure G-4. Wall and Footing Reinforcement

ABUTMENT AND RETAINING-WALL REINFORCEMENT

G-26. Abutments and retaining walls have several sets of forces acting on them *(Table G-2* and *Figure G-5)*. First, there are the vertical loads placed on the stem and footing by bridge and soil loads. Second, there are the horizontal loads that result from the tendency of the bridge and soil loads to push the abutment or wall into the gap. Finally, there are horizontal bridge loads that tend to push the abutment away from the gap. The steel reinforcement is located in all areas of tension in these structures *(Figure G-6, page G-10)*.

Table G-2. Maximum Reinforcement Ratio

f′c (ksi)	Yield Strength (f_y) (ksi)									
	20	24	28	32	36	40	44	48	50	60
2.0	0.052	0.045	0.037	0.037	0.030	0.030	0.022	0.022	0.022	0.015
2.5	0.067	0.060	0.045	0.045	0.037	0.037	0.030	0.030	0.030	0.022
3.0	0.082	0.067	0.060	0.052	0.045	0.037	0.037	0.037	0.030	0.030
3.5	0.097	0.082	0.067	0.060	0.052	0.045	0.045	0.037	0.037	0.030
4.0	0.105	0.090	0.075	0.067	0.060	0.052	0.052	0.045	0.045	0.037
4.5	0.120	0.105	0.090	0.075	0.067	0.060	0.052	0.052	0.045	0.037
5.0	0.135	0.112	0.097	0.082	0.075	0.067	0.060	0.060	0.052	0.045
5.5	0.150	0.127	0.105	0.090	0.082	0.075	0.067	0.060	0.060	0.052
6.0	0.165	0.135	0.112	0.105	0.090	0.082	0.075	0.067	0.067	0.052

LEGEND:
f′c (ksi) = compressive strength

PRESTRESSED AND POSTSTRESSED CONCRETE

G-27. The principles for placing reinforcement in prestressed and poststressed concrete beams are the same as in normally reinforced concrete. However, the reinforcing steel is placed in tension when the beam is unloaded. This tension in the reinforcing steel causes compression in the concrete. The compression on the beam lowers the neutral axis and uses more of the compressive strength of the concrete to make the beam stronger. The two ways of creating tension in the steel reinforcement (installing tendons) are by prestressing or poststressing the steel.

G-28. In prestressed concrete, the tendons are placed in the bottom of the formwork, pulled very taut, and covered with the plastic concrete. Once the concrete gains sufficient strength, the tension on the tendons is released. When released, the tendons try to resume their original length, thus introducing compression into the lower portion of the beam. The compressive stress in the bottom of the beam counteracts the tension caused when the beam is loaded. The only difference between prestressing and poststressing is that in poststressing the tendons are stretched to the desired tautness after the concrete has reached the desired strength.

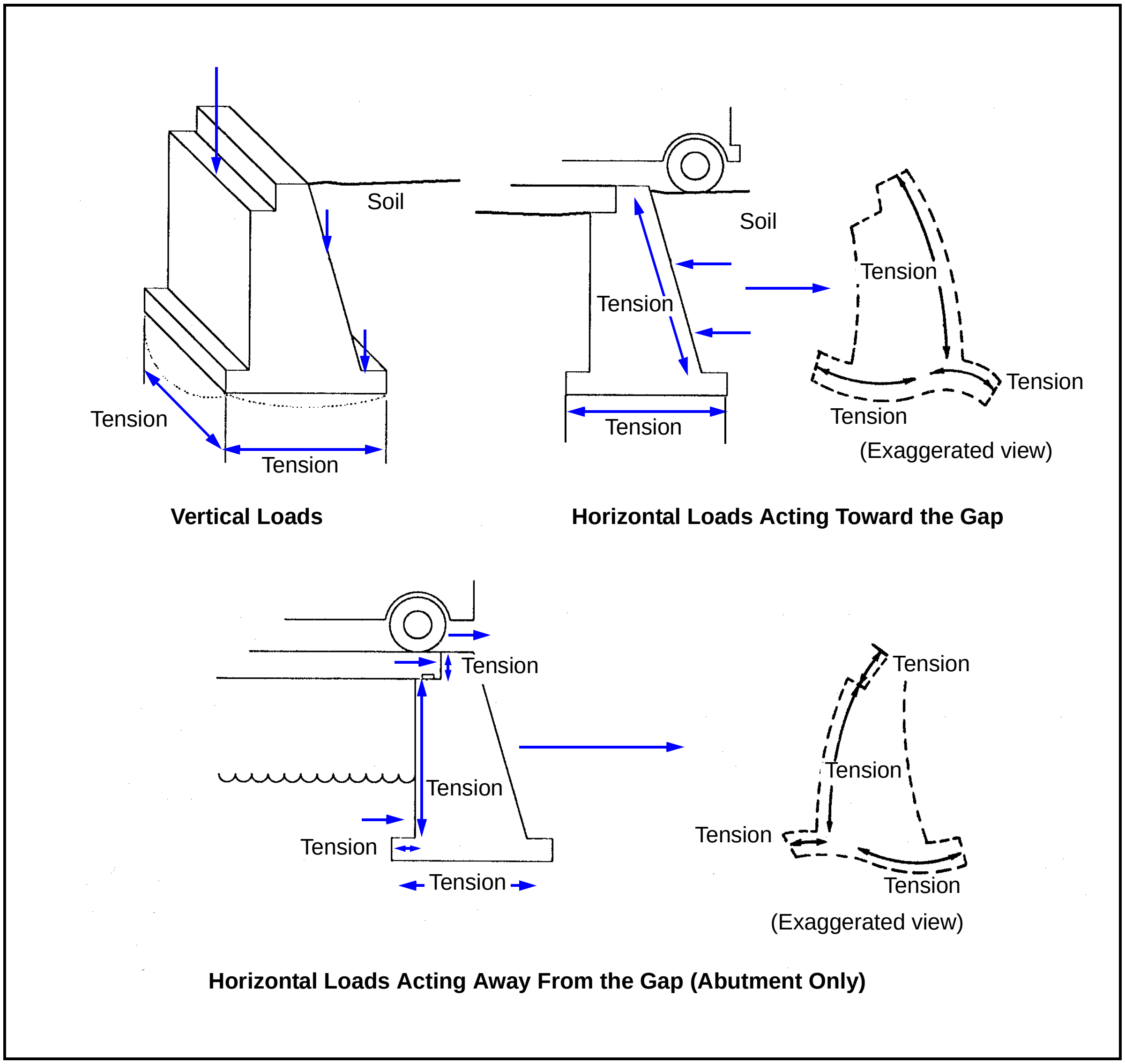
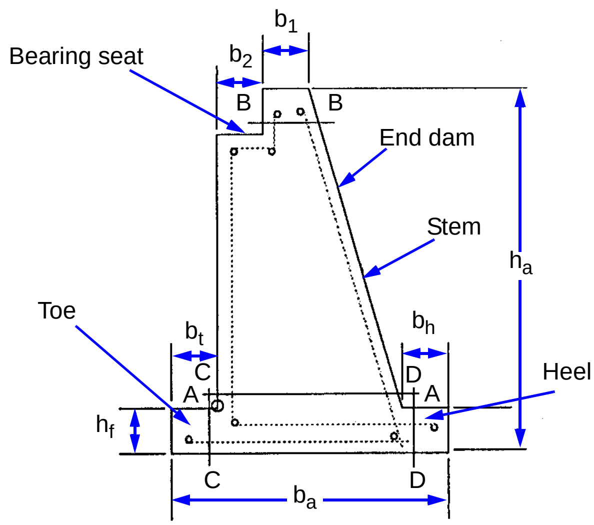


Figure G-5. Tension Forces in a Retaining Wall or Abutment



LEGEND:

h_a = abutment height
h_f = footing height (1′ to 2′)
b_1 = minimum of 12′
b_2 = bearing seat width (minimum 0.75′)
b_t = toe width (0.75′ to 1.5′ and 0.75 h_f)
b_a = footing width (0.4) h_a to 0.6 h_a)
b_h = heel width (0.75′ to 1.5′ and 0.75 h_f)

Figure G-6. Typical Reinforced Concrete Abutment